An Error Free Passive UHF RFID System using a New Form of Wireless Signal Distribution

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Abstract — **A wide area and error free ultra high frequency (UHF) radio frequency identification (RFID) interrogation system based on the use of multiple antennas used in cooperation to provide high quality ubiquitous coverage, is presented. The system uses an intelligent distributed antenna system (DAS) whereby two or more spatially separated transmit and receive antenna pairs are used to allow greatly improved multiple tag identification performance over wide areas. The system is shown to increase the read accuracy of 115 passive UHF RFID tags to 100% from <60% over a 10m x 8m open plan office area. The returned signal strength of the tag backscatter signals is also increased by an average of 10dB and 17dB over an area of 10m x 8m and 10m x 4m respectively. Furthermore, it is shown that the DAS RFID system has improved immunity to tag orientation. Finally, the new system is also shown to increase the tag read speed/rate of a population of tags compared with a conventional RFID system.**

Keywords - distributed antenna system (DAS); passive ultra high frequency (UHF) radio frequency identification (RFID); received signal strength indicator (RSSI); range; nulls; read success rate; read rate; tag orientation

I. INTRODUCTION

Radio Frequency Identification (RFID) technology has recently attracted a high level of research interest. The ability of RFID to replace barcodes, allowing storage of information about the tagged object as well as remote reading and location sensing, has great potential. However the overall uptake of RFID technology has been slower than many predicted. One reason for this is the limited reliable range of passive ultra high frequency (UHF) RFID system operating in real environments [1]. As a result, several studies have focused on enhancing passive RFID coverage, for example by using phased array techniques [2]. Recently it has been shown that an improved area of coverage can be achieved by employing an optical distributed antenna system (DAS) so that the effective field of view of an RFID reader can be greatly expanded [3].

By expanding the range of view of a single RFID reader, as well as improving the likelihood of successful tag detection, one can envisage RFID systems with wide coverage areas as opposed to the portal systems currently in use today, where sensitivity constraints require the objects to pass close to the reader antennas for detection.

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In this paper we extend the ideas first presented in [3]. By using a co-axial rather than fibre distribution system we report a full study of the performance improvements of the DAS RFID system over a conventional RFID system. The problems of multipath nulls and tag orientation as well as tag throughput are addressed. It is shown that the DAS RFID system can provide a wide area of coverage, with error free tag detection and a high tag throughput in a realistic environment.

The structure of this paper is as follows: Section II provides a brief summary of related work. In Section III, a description of the new co-ax DAS RFID system is provided. Section III also analyses tag orientation and the multi-path fading dependence of tag detection accuracy and presents the experimental methodology and discusses the results for an error free passive RFID coverage over a wide area DAS RFID system. Section IV presents tag read rate performance in passive RFID system. Finally, in Section V, conclusions are drawn from the presented results.

II. RELATED WORK

One of the main challenges facing passive RFID has been to develop the technology so that tags can be read successfully with high reliability over a wide area. Several studies have been undertaken to improve passive UHF RFID system performance in terms of coverage, read success rate and read rate [4-6]. A key problem for RFID systems operating in real environments is multipath fading. Due to the narrow bandwidth of the interrogation signal, this can result in nulls where tags cannot be read. Poor tag orientation with respect to the reader antennas can also result in an unfavourable link loss and reduce tag reads.

One approach to address this problem, makes use of a passive UHF RFID system with phased array of antennas (i.e. the antennas are in the near field region of one another) [2]. This allows phased array techniques to be employed, for example digital beam forming to maximise the link budget. While the narrow beamwidth of the antenna reduces multipath, the phased array antenna technique is only applied in the receiver path, so downlink fading remains.

Alternatively fading can be reduced by maintaining a small separation between the interrogator antennas and the tags compared to the distance to the closest reflector. The short range results in a large link budget to minimise tag

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orientation problems. Therefore, in conventional RFID tag systems, operators aim to remove nulls from areas where tags are to be detected in order to ensure efficient performance. However, that aim can normally be secured only by using short antenna distances. Even then, it is impossible to achieve completely accurate detection. Hence conventional RFID systems require numerous antennas and RFID readers as shown in Fig. 1a. The technique presented in this paper (DAS RFID) does not attempt to remove the nulls; instead radio frequency (RF) techniques and multiple antennas are used to time vary the location of the nulls, moving them away from the tag and facilitating a successful reading using a technique we call intelligent DAS processing. In this way, it has become possible to achieve a 100% read success rate (i.e. error free operation) of multiple tags over a large area. A comparison of conventional system and a DAS RFID system is shown in Fig. 1. As a result of the technique, antenna diversity can be employed to improve immunity to tag orientation problems.

The rate at which tags can be read, the tag read rate, has also been a major challenge in passive RFID systems due to tag collisions that occur when multiple tags backscatter simultaneously [7-9]. As a result, UHF RFID operators have employed a variety of anti-collision protocols to overcome tag collisions. For example, the Class 1 Gen 2 UHF RFID protocol is based on the ALOHA protocol which is fundamentally limited in its capabilities. More efficient algorithms exist but limited processing resources on passive tags prevent their use in this application. To date, a number of studies have addressed the tag collision problem in literature [10-15]. The studies have focused on how the ALOHA algorithm can be modified or enhanced to improve tag read rate. For instance, many researchers have proposed dynamic Q ALOHA algorithms and enhanced dynamic framed slotted ALOHA algorithms. We, however, show that an enhanced read rate can be achieved in the UHF RFID system by using intelligent DAS processing, applied over a dynamic Q ALOHA algorithm. This improvement is due to both a reduction in the number of collisions (result of dynamic grouping) and an improvement in the read success rate (result of enhanced radio coverage). The dynamic grouping is due to the fact that the intelligent DAS processing technique moves the dead spots (nulls) around the field, therefore only a portion of the total tag population is addressed at any instant. Since the ALOHA algorithm is more efficient with smaller populations (here we define efficiency as the number of tag successful reads to collided and empty to slots), DAS RFID is able to provide a high sustained tag throughput with large tag populations. It has been modelled to outperform conventional RFID readers.

III. NULLS/DEAD SPOTS AND TAG ORIENTATION IN PASSIVE RFID SYSTEM

As shown in Fig. 2, the co-ax DAS RFID system developed in this work is composed of a custom RFID prototype reader containing a R1000/R2000 Impinj transceiver [16], DAS processing unit, four antenna pairs each containing separate transmit (Tx) / receive (Rx) elements and multiple passive tags. 30m of LMR-400 co-ax cable is used as the transport medium between the RFID reader and the antennas. The co-ax DAS is designed to operate over the global RFID operating frequency range from 860MHz to 950MHz.

In the downlink, DAS processing is applied to RF signals from the RFID reader. The RF signal is then carried over four 30m co-ax links before transmission at each antenna pair. Here 30m links are used to represent a small DAS. However, modelling shows that, operation over >100m of co-ax (for example, using Belden 7977A co-ax cable with 2.5dB attenuation/100ft) is possible, allowing the RFID reader to be remote from the antennas, for instance in an IT closet. The uplink operates in a similar manner, taking signals from an antenna at the antenna pair, and passing them back to the reader.

The antennas used in this work are directional, circularly polarized ISM band (860MHz - 950MHz) antennas with a 6dBi gain, a 3dB beam width of 69° in azimuth, 67° in elevation, and 0° down tilt. A 2 m separation between the Tx and Rx antennas provides isolation between the uplink and downlink.

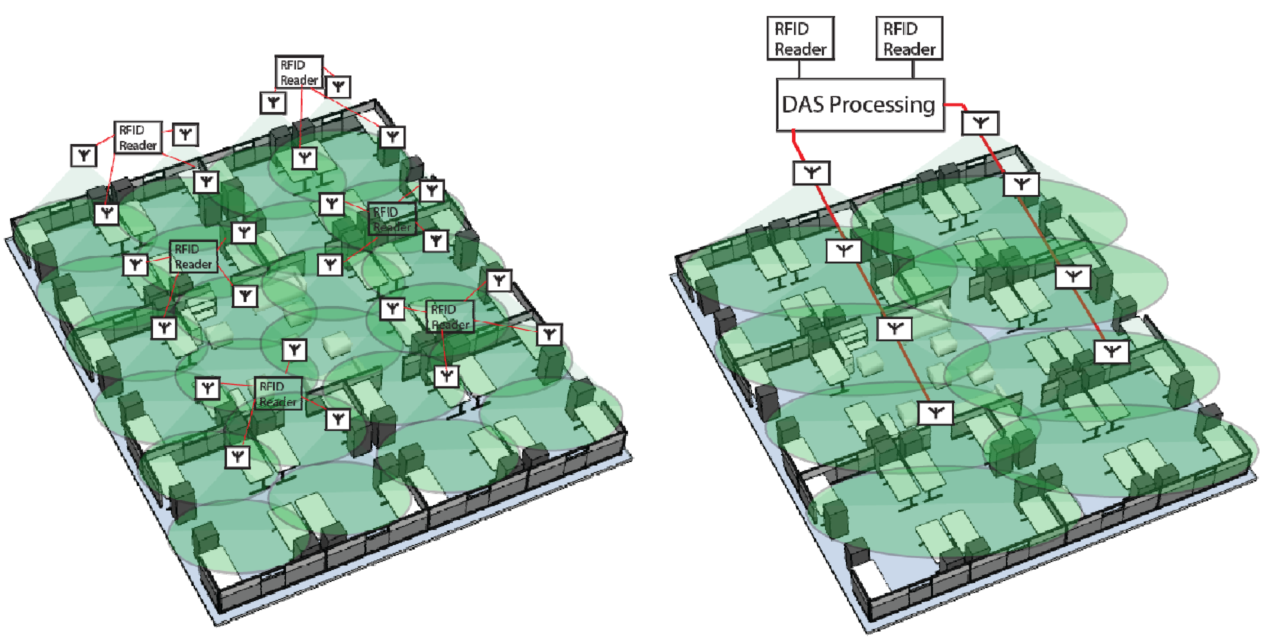

Fig. 1. A comparison of conventional RFID system and our DAS RFID system; (a) conventional RFID system requires lots of antennas and RFID readers (left). (b) our DAS RFID system requires fewer antennas with better range (right).

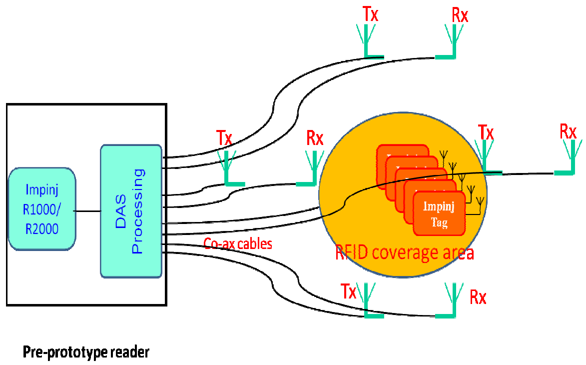

Fig. 2. A protoype DAS RFID system layout based on Impinj R1000/R2000.

When a passive RFID tag receives sufficient power to power up its internal IC, it returns its unique ID by backscatter modulation of the reader signal in response to a carrier frequency between 865.7MHz and 867.5MHz using phase shift keyed (PSK) modulation.

A set of experiments are carried out to demonstrate the tag read accuracy of a conventional RFID system and our new DAS RFID system. Fig. 3 shows a plan view of the physical arrangement of the four antenna pairs used in this work and of the measurement locations over a 10m x4 m area in our laboratory. The laboratory area is bounded by solid walls at the left and right extremes of the figure and contains many equipment racks which will produce multipath so may be considered to be a realistic test environment for real world applications. 150 Impinj Monza-4 [17] Class1 Gen2 UHF passive tags are placed at a height of 2m on a 25cm grid interval over a 10m x 4m area as shown in Fig. 3. The tags are orientated such that their antennas are vertically polarized and are held fixed throughout the experiments. The interrogator antenna pair locations are chosen to provide overlapping coverage and the heights are matched to the tags such that everything is on a plane 2m above the floor. A +35dBm effective isotropically radiated power (EIRP) is transmitted from each transmit antenna. The received signal strength

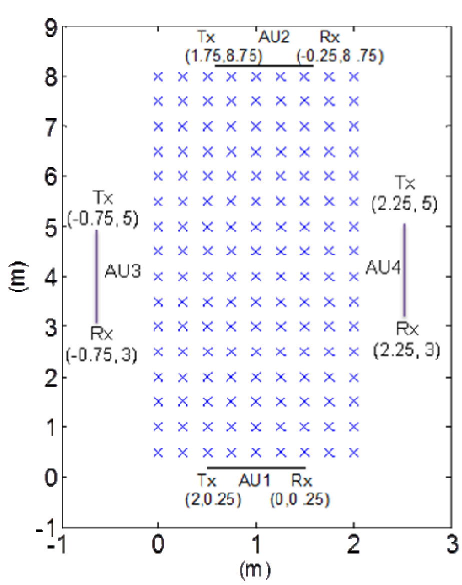

Fig. 3. 150 Impinj Monza-4 tags are placed at a height of 2m on a 25cm grid interval over a 10m x 4m area. The positions of the antennas are indicated in meters in the form of (x, y) coordinates. Blue crosses represent the tag locations.

indicator (RSSI) values of each tag are recorded over a number of inventories for conventional single and four antenna systems as well as the new four antenna DAS RFID system.

As shown in Fig. 4, the null locations where a tag could not be read are shown by read crosses while successful reads are shown by the corresponding RSSI values in the figure. It can be seen that the conventional single and four antenna RFID systems give a tag success rate of 81.3% and 87.3% respectively. However, the DAS RFID with intelligent processing gives a 100% read accuracy. It is also apparent that the returned signal strength is higher and more uniform in the case of the DAS RFID system. Further analysis shows that the mean RSSI is improved by 17dB.

Fig. 5 shows the successful tag detection rate as a function of read range over a conventional single antenna system (RSSI distribution is shown in the left plot in Fig. 4). It can be seen from Fig. 5 that it is only possible to achieve accurate tag detection (ie. 100% tag read success rate) within a range of 2m from the antenna. It is worth noting that this reliable tag detection range will be even smaller and difficult to achieve when tags are placed in multiple orientations, and that this configuration represents something of a best case. Therefore, in order to cover a large area one would be required to distribute

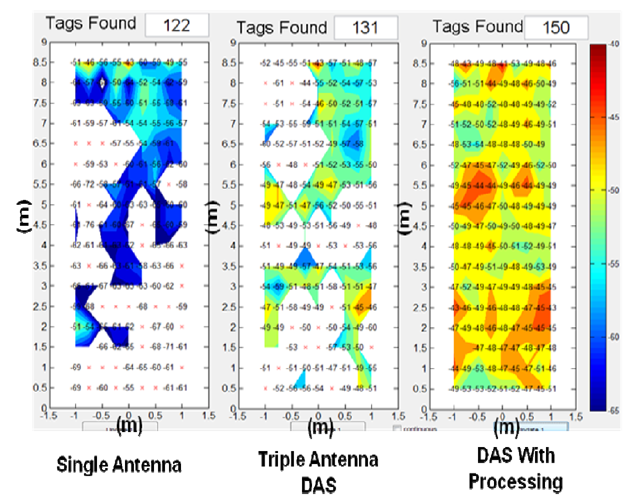

Fig. 4 New DAS RFID system gives an error free performance due to intelligent RF signal processing. Null locations are shown by read crosses while successful reads are shown by the corresponding RSSI values.

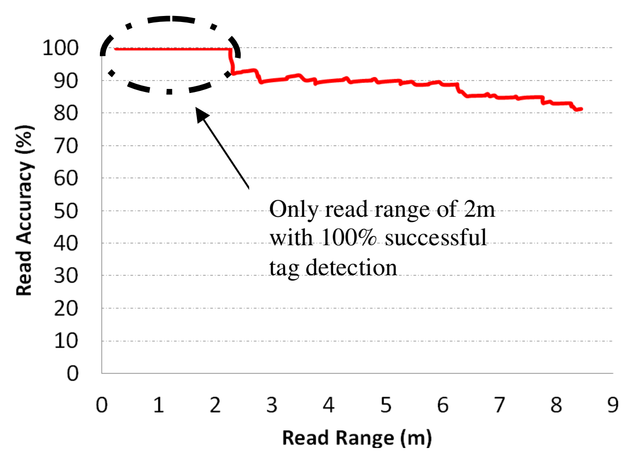

Fig. 5. Tag detection accuracy as a function of read range for a conventional single antenna system.

antennas at least every 4m when using a conventional RFID system (as depicted schematically in Fig. 1). Hence the conventional passive RFID system scales poorly to cover large areas. However, the new DAS RFID system is capable of enabling a wide area coverage using fewer antennas but with better range.

The tag read accuracy results discussed so far have used tag antennas matched and fixed in orientation to the reader antennas. However, in practice, tag orientation is likely to be random with respect to the reader antennas. It has been shown previously that this can have a strong effect on the read accuracy and RSSI [18]. The effect of tag orientation on tag read accuracy and RSSI is reduced for the DAS RFID approach due to antenna diversity combined with intelligent DAS processing. For example, consider a typical dipole tag with a radiation pattern shown in Fig. 6a. If the RSSI is summed from 3 equidistant antennas, in the best case directions (0°, 120°, 240°) and worst case (0°, 90°, 180°), the orientation dependence of the RSSI is reduced from 50dB to 3dB (best case) and 10dB (worst case) using the DAS RFID, as shown in Fig. 6b. In reality multipath effects will serve to reduce the orientation dependence further.

In order to demonstrate this proof of concept, 192 tags are placed in x, y and z orientations (ie. 64 tags in each orientation) over a 10m by 4m area in the laboratory. Figs. 7 and 8 show the probability of a failed read at each tag location as well as the RSSI distribution of the 192 tags for a conventional four antenna RFID system and new DAS RFID system respectively. It is clear from Fig. 7 that the conventional system suffers heavily from RF signal fading and tag orientation, resulting in several read failures. However, the DAS RFID system is shown to have eliminated or minimised the effect of fading and the tag orientation effect. As a result, error free coverage (ie. 100% read success rate) of 192 tags is achieved in the DAS RFID system compared with <80% in the conventional RFID system. It is worth noting that the DAS RFID system gives no read errors over 1 million attempts when the system is configured to operate continuously as shown in Fig. 8.

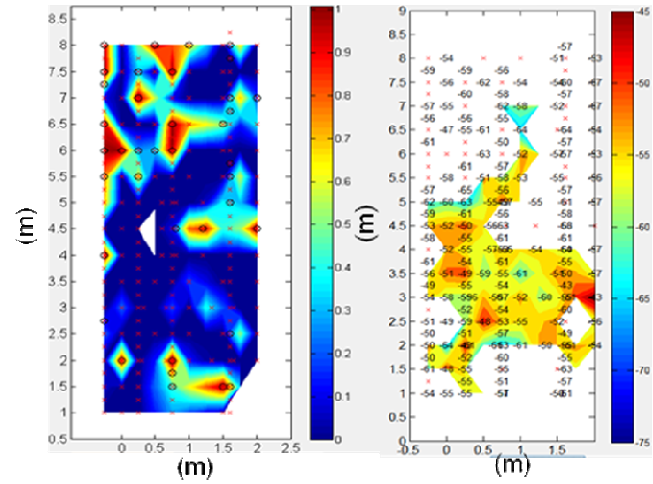

Fig. 7. Conventional system gives several read failures due to RF signal fading; (a) probability of failed reads for a conventional RFID system (left). (b) RSSI distribution for a conventional RFID system (right).

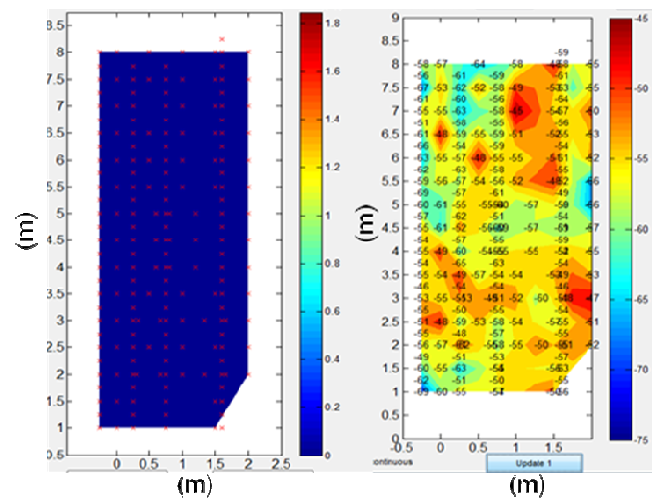

Fig. 8. New system gives an error free performance due to intelligent RF signal processing; (a) probability of failed reads for a DAS RFID system (left). (b) RSSI distribution for a DAS RFID system (right).

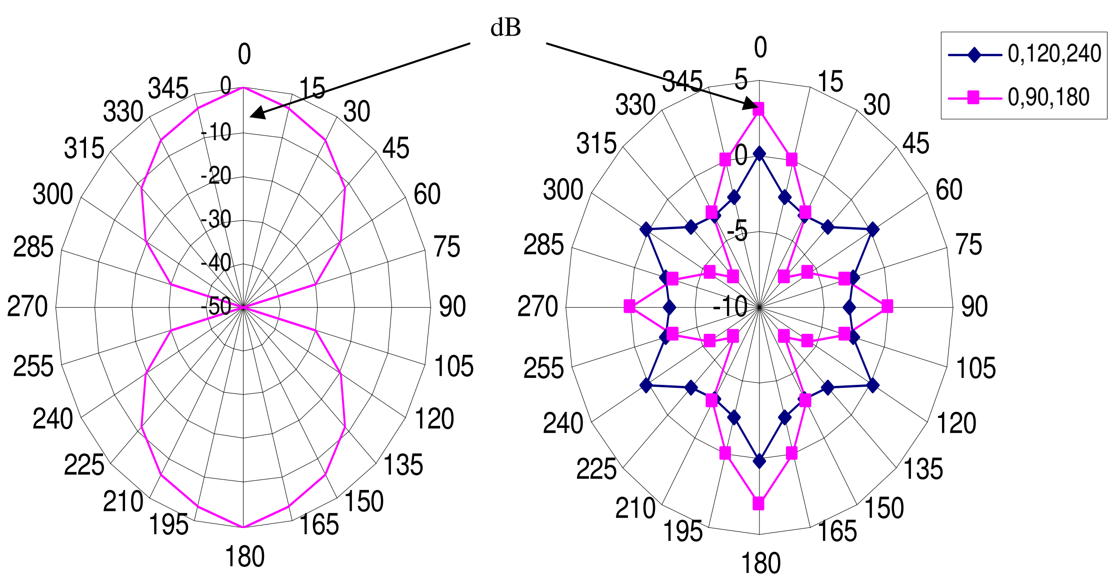

Fig. 6. (a) Typical tag dipole radiation pattern, and (b) effective radiation pattern when three read antennas are used at the indicated angular separations. Note the different radial scales.

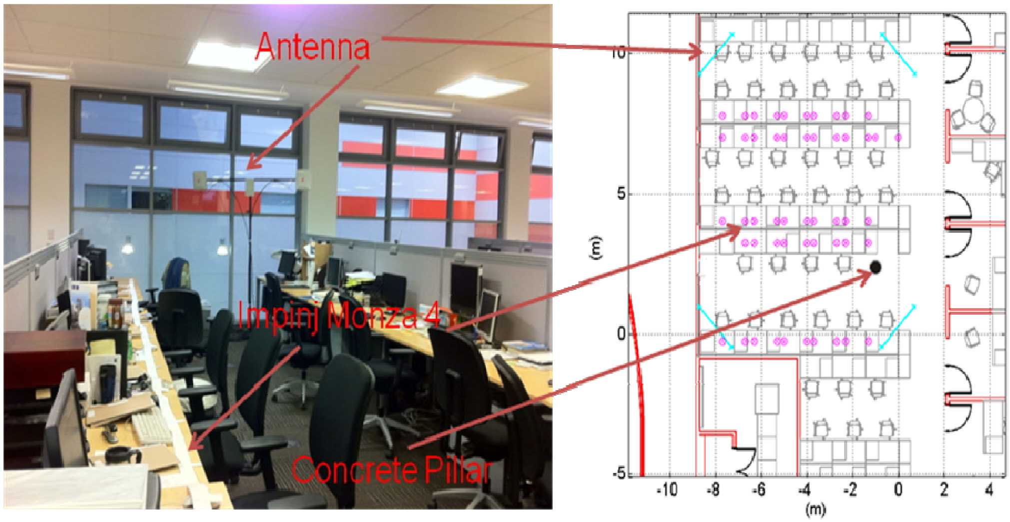

Fig. 9. Four antennas are distributed over a 10m x 8m office area and 115 Impinj Monza4 tags are placed on desks.

We have also carried out a trial to study the feasibility of this new RFID system over a wide area in an open plan office environment. As shown in Fig. 9, the DAS RFID system is distributed over a 10m x 8m open office area and 115 Impinj Monza-4 tags are placed on desks. Antenna and tag locations are also shown in the figure.

Figs. 10 and 11 show the RSSI distributions of successfully read tags for a conventional and DAS RFID systems respectively. The cumulative probability density function (CDF) for the received signal strength of 115 tags is shown in Fig. 12. The CDF values indicate the fraction of tag locations where the RSSI is less than or equal to the x-axis value. In this case 42% of the tags placed on the desks could not be detected by the conventional RFID system. However with the intelligent DAS processing, all the tags could be detected, there is also a significant improvement in the received power when the intelligent DAS processing is employed.

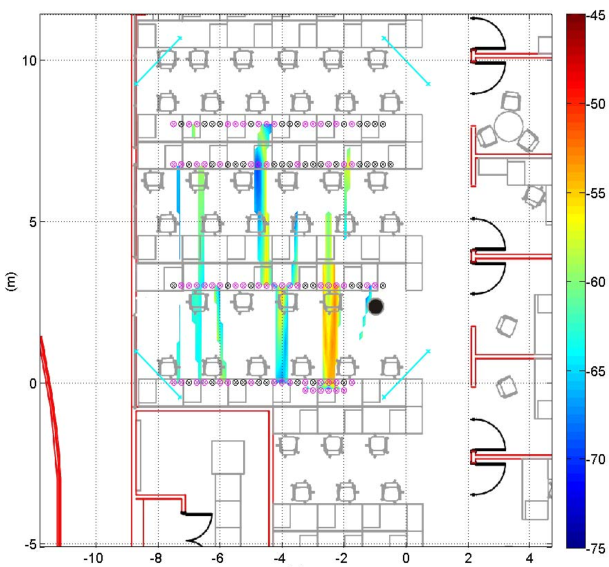

Fig. 10. Plot of RSSI distribution for a conventional RFID system. Conventional system gives several read failures due to RF signal fading. Pink circles represent the locations of successfully read tags while black circles represent the locations of nulls.

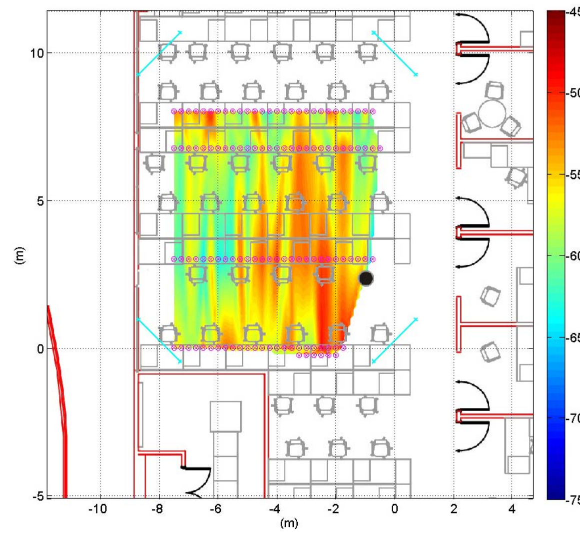

Fig. 11. Plot of RSSI distribution for a DAS RFID system. New system gives an error free performance due to intelligent RF signal processing. Pink circles represent the locations of successfully read tags while black circles represent the locations of nulls.

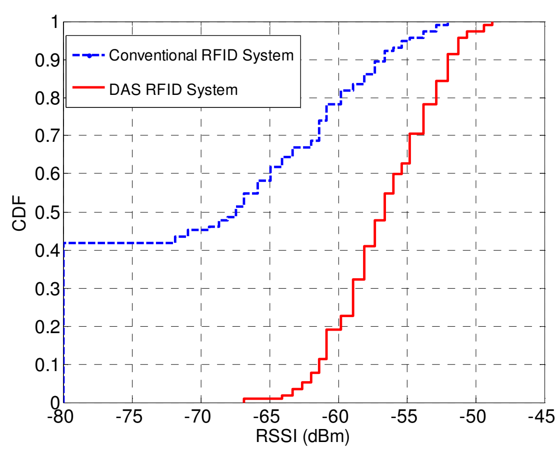

Fig. 12. Demo of reading 115 tags on desks over a 10m x 8m office area. The CDF values indicate the fraction of tag locations where the RSSI is less than or equal to the x-axis value. The passive DAS RFID gives a 100% read success rate as opposed to a 58% read success rate in a conventional system over a 10m x 8m office area.

IV. TAG READ RATE IN PASSIVE RFID

In the previous section, it has been shown that passive RFID coverage and read success rate of multiple tags can be improved by employing a multiple antenna DAS. In a wide area RFID system where many tags may fall in the field of view, the read rate will also be of great importance.

The tag read rate of an RFID system is governed by the modulation scheme which is generally restricted by the tag sensitivity, and the anti-collision protocol. To date, a variety of ALOHA based algorithms have been proposed in the literature to avoid collisions when multiple passive RFID tags are present. One of the simplest and most common algorithms is the dynamic Q frame slotted ALOHA [19-21].

A. *Read Rate/Speed Enhancement using Intelligent DAS Processing over R1000/R200 Dynamic Q Algorithm*

The read rate is investigated using a probabilistic algorithm that is commonly employed in commercial RFID readers, for the number of occupied successful slots (with useful tag reads), empty slots (with no tag response) and collision detections (result of more than one tag backscatter) by the reader. In the system, collisions cause backoffs and if there are too many collisions the number of available time slots is increased.

The tag inventory cycle comprises a set of tag read rounds to read multiple tags. A tag read round has a set of time slots, determined by the Q-bit random number in the tag slot counter. At the start of the count all tags randomly set their tag slot counter. During the count all tags decrement their slot counter until the tag slot counter is 0. When this occurs they backscatter their ID in the slot. During the inventory cycle read tags have the inventorised bit set so that they do not compete in subsequent cycles, thereby speeding up the inventory.

It is necessary to estimate the number of tags in the field in order to achieve optimum read rate/speed. This is because the optimum rate can only be achieved by issuing the optimum Q-factor in the Gen 2 protocol. The optimum total number of slots (determined by 2^Q) is equal to the total number of active tags in the field as a larger value of Q (larger number of slots) will lead to fewer collisions but also reduce the read rate due to more empty slots, on the other hand, a smaller value of Q will lead to more collisions.

Due to the fact that more than one tag may load the same Q bit random number into its slot counter, this approach results in a number of successful tag replies (successful slots), a number of slots that contains no replies (the empty slots) and a number of collided tag replies (the collided slots) as shown in Fig. 13. Successful, empty and collided slots can be detected by the reader, and each have a different duration. This information can then be used to estimate the number of tags in the reader's field of view and to select the optimum Q value. The elements of successful, collided and empty slots are shown in Fig. 13. The slots times are calculated using the Gen2 parameters listed in Table 1. The link timing parameters, T_1, T_2, T_3 and T_4 can be found in [22]. A successful slot time, Ts is calculated to be 1260.3µs while an empty slot time, Te and a collided slot time, Tc are calculated to be 221.87µs and 256.25µs respectively.

TABLE 1 THE GEN 2 PROTOCOL PARAMETERS USED IN THE SIMULATIONS

Parameter	Description	Value
Tari	time interval for a data-0 in interrogator-to-tag signalling	6.25µs
RTcal	interrogator-to-tag calibration symbol	2.5Tari
TRcal	tag-to-interrogator calibration symbol	33.3µs
M	number of subcarrier cycles per symbol	2
DR	divide ratio	64/3
BLF	backscatter link frequency	640kHz

The expected number of empty slots (N_0) in an inventory round is then given by [23]

$$N_0 = 2^Q\,(1-1/2^Q)^t \qquad (1)$$

where t is the total number of tags in the field and 2^Q is the total number of slots in a frame.

Similarly, the expected total number of successful slots (N_1) is given by

$$N_1 = t\,(1-1/2^Q)^{(t-1)} \qquad (2)$$

Hence, the expected total number of collided slots is given by

$$Nc = 2^Q - 2^Q\,(1-1/2^Q)^t - t\,(1-1/2^Q)^{(t-1)} \qquad (3)$$

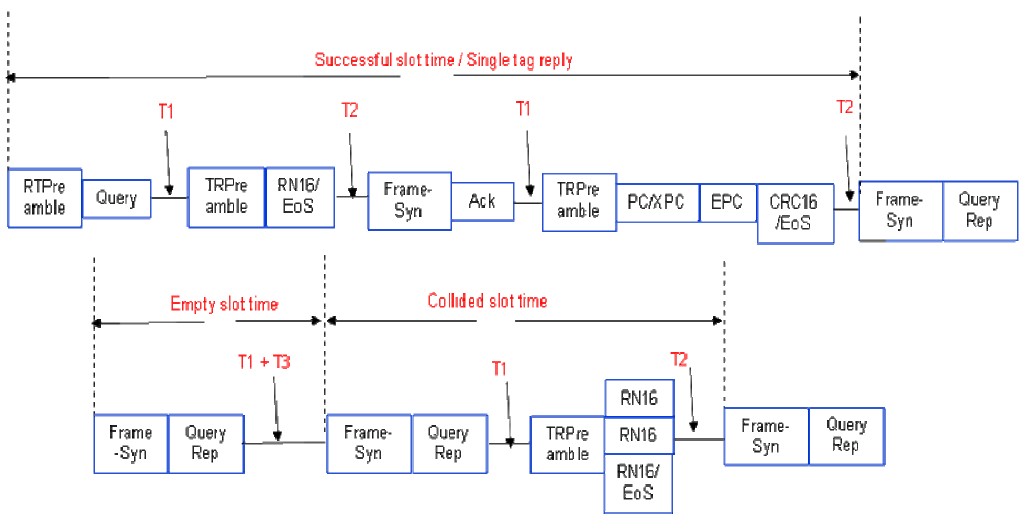

Fig. 13. Estimating/calculating the read speed/rate using information from expected empty, successful and collided slots. A detailed description of the frames and elements is provided in the EPCglobal standard [22].

Therefore, by solving (1), (2) and (3) the total number of tags can be estimated from N_0, N_1 and Nc as these values are presented to the reader. The total time for an inventory round is given by

$$T_{tot} = N_1\, Ts \;+ N_0\, Te + Nc\, Tc \qquad (4)$$

where Ts, Te and Tc are the successful slot time, empty slot time and collided slot time respectively.

The total number of tags can be estimated in three different ways; using the information from the empty slots (1), from the successful slots (2) and from the collided slots (3). Here, a Monte Carlo (MC) simulation is used to determine the maximum tag throughput for the parameters in Table 1. The simulation is performed 1,000 times and the results are averaged over the 1,000 iterations to cope with the random distribution of the Q factor (Q bit random numbers) which controls the process. In this simulation, an initial Q value of 9 is assumed to be transmitted from the reader and hence the frame size is 512 slots (2^9). We then estimate the number of tags in the field and the successful slots over a time period using the observable parameters as well as the optimum tag rate equation given in [14]. This model estimates a maximum read rate of 610 tags/sec in passive RFID with the profile specified in Table 1. However, in practical system the read rate will slightly differ from the theoretical limit due to data transmission errors as a result of poor signal to noise ratio (SNR).

Hence we have developed and built this profile in our RFID prototype to allow a comparison the read rate performance, with the protocol limited maximum. An inventory using the dynamic Q algorithm is performed with the system operating as a conventional (where a four pair antenna system is used to transmit signals simultaneously) and the four pair antenna DAS RFID system (where intelligent DAS processing is applied over a four pair antenna DAS system).

As shown in Fig. 14, the conventional RFID system achieves a tag read rate of 318 tags/sec and the DAS RFID provides a read rate of 406 tags/sec. Thus, a 28% improvement in tag read speed is achieved. Moreover, an initial read rate of > 400 tags/sec is sustained for a greater proportion of the total tag population using the DAS RFID system. The DAS RFID system also gives a total data transmission error of 28.3% (ie. ratio between cyclic redundancy check (CRC) errors and successful reads) compared with a 42.8% data transmission error in a conventional RFID system. These data transmission errors explain the deviation from the theoretical predictions. However, the CRC errors are recoverable since they are detected and subsequent attempts are successful in the DAS RFID system.

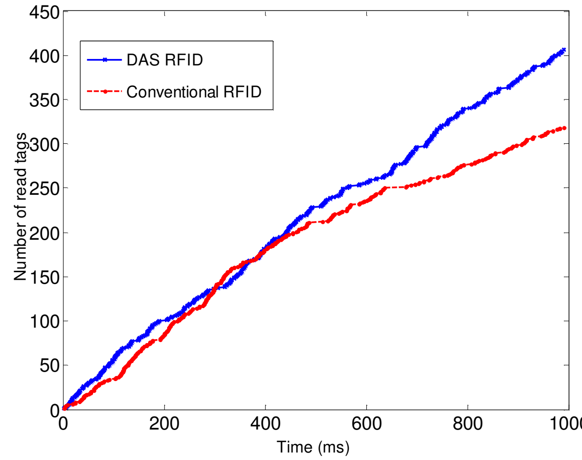

Figure 14. A plot of number of read tags against time for a conventional RFID system and an optimised DAS RFID system. Conventional antenna system reads tags at a rate of 318 tags/sec while optimised DAS RFID is at a rate of 406 tags/sec. Hence, a 28% improvement in tag read speed is achieved.

The improvement in the tag read rate is due to the number of collisions within each inventory round being reduced and read success rate being enhanced using the intelligent DAS processing technique as it moves the nulls around the field. Hence, only a certain number of tags are active at any time.

Fig. 15 shows a plot of number of RN16 timeouts in each inventory round against time for the conventional RFID system and the DAS RFID system. It is again shown that DAS RFID encounters fewer collided and empty slots compared with a conventional RFID system. The results clearly illustrate that a high sustained tag throughput with large tag populations can be obtained in a DAS RFID that can outperform conventional RFID readers.

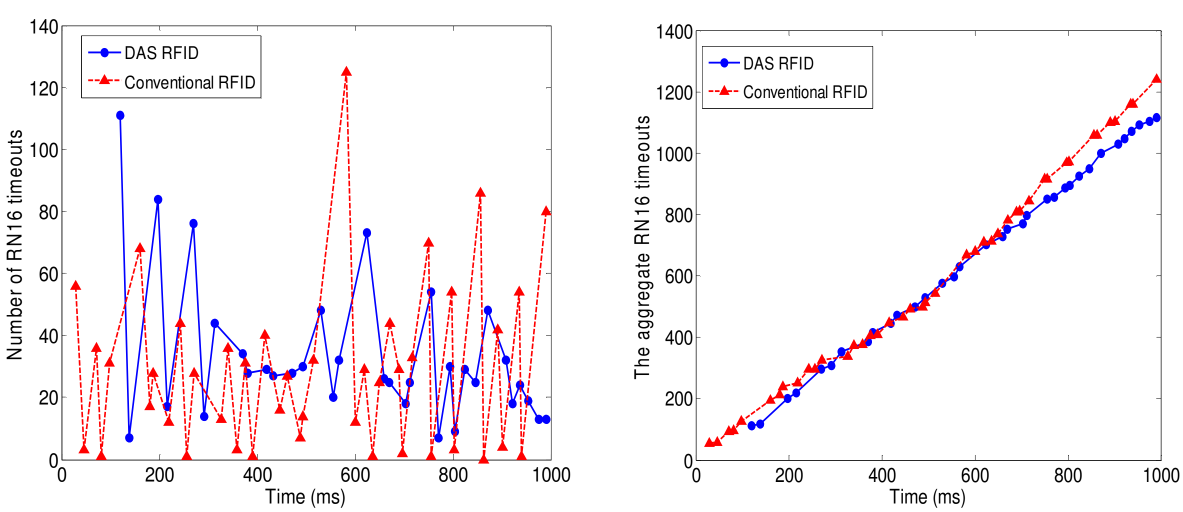

Fig. 15. (a) a plot of number of RN16 timeouts in each inventory round against time and (b) a plot of aggregate number of RN16 timeouts against time, for both conventional RFID system and DAS RFID system.

The demonstrator also shows that while an enhanced tag read rate is achieved in the DAS RFID system, the initial tag read rate is sustained for a greater proportion of the total tag population. This improvement is due to both a reduction in the number of collisions (result of dynamic grouping) and an improvement in the read success rate (result of enhanced radio coverage).

The tag read speed/rate can be improved further by increasing the backscatter link frequency (BLF) to the 640kHz maximum, and FM0 (bi-phase space) coding for a high data rate (640kbps). However, with increasing link frequency and data rate, the energy per bit is reduced, so for a fixed SNR, the link error rate increases. Therefore, the sensitivity is reduced by as much as 20dB in changing from 40kbps to 640kps. However, due to the increased system margin of the DAS RFID system we have successfully demonstrated a 640kHz link frequency with a 320kbps data rate.

V. CONCLUSION

This paper has focused on improving the read accuracy, speed of tag detection and enhancement in stability of a RFID system demonstrator suitable for testing in realistic environments.

We have shown that improved coverage can be achieved in detecting passive UHF RFID tags. Using antenna diversity combined with intelligent DAS processing in a multi-antenna co-ax DAS RFID system, a significant improvement in the power of the signals returned from the tag and the tag success rate can be obtained.

We have also shown that we can read tags with 100% success rate (ie. error free operation) compared with <60% accuracy in a conventional commercial passive RFID system in office environment (currently, this has been demonstrated over a 10m by 8m open office area). Finally, we have also demonstrated a 28% improvement in tag read rate.

The performance enhancement has been demonstrated in Europe frequency band (ie. 865-868MHz). It is anticipated that a similar improvement can be achieved across the Global RFID frequency band.

We believe that this improvement in coverage of a passive RFID system will allow passive RFID to be used in new applications such as passenger tracking and document tracking.

REFERENCES

[1] K. Finkenzeller, *RFID Handbook: fundamentals and applications in contactless smart cards and identification*, 2nd ed. New York: Wiley, 2003.

[2] [Online]. Available: http://www.mojix.com/

[3] S. Sabesan, M. Crisp, R. Penty, I. H. White, "Demonstration of Improved Passive UHF RFID Coverage using Optically-Fed Distributed Multi-Antenna System ," in *Proc IEEE International Conference on RFID 2009*, pp. 217-224, 2009.

[4] J. Curty, N. Joehl, C. Dehollain and M. Declercq, "Remotely powered addressable UHF RFID integrated system," *IEEE Journal of Solid-State Circuits,* vol. 40, No. 11, 2005.

[5] [35] P. Khannur, X. Chen, D. Yan, D. Shen, B. Zhao, M. Raja, Y. Wu, R. Sindunata, W. Yeoh and R. Singh, "A universal UHF RFID reader IC in 0.18-um CMOS technology," *IEEE Journal of Solid-State Circuits*, vol. 43, No. 5, pp. 1146-1155, 2008.

[6] J. Kim, W. Lee, E. Kim, D. Kim and K. Suh, "Optimized transmission power control of interrogators for collision arbitration in UHF RFID systems," *IEEE Communications Letter,* vol. 11, No. 1, 2007.

[7] J. R. Cha and J. H. Kim, "Dynamic framed slotted ALOHA algorithms using fast tag estimation method for RFID system," *CCNC 2006*, vol. 2, pp. 768-772, 2006.

[8] S. Lee, S. Joo and C. Lee, "An enhanced dynamic framed slotted ALOHA algorithm for RFID tag identification," *MobiQuitous 2005*, pp. 166-172, 2005.

[9] Siti Mahfuzoh Wasikon and Zurinah Suradi, "A Framework of Tag Anti-collision Algorithm for Fast Identification in RFID System", Proceedings of the International Conference on Computer and Communication Engineering 2008, Malaysia, 2008

[10] H. Vogt., Multiple Object Identification with Passive RFID Tags. IEEE International Conference on Systems, Man and Cybernetics. October 2002.

[11] J.-M. Seol, S.-W. Kim, "Efficient Collision-Resilient RFID Tag Identification using Balanced Incomplete Block Design Code", in Proceedings of 6th IEEE International Conference on Computer and Information Technology (CIT'06), Sept. 2006, pp. 220.

[12] J. R. Cha and J.H. Kim, "Novel anti-collision algorithms for fast object identification in RFID system", *IEEE International Conference on Parallel and Distributed Systems*, 2005.

[13] C. Floerkemeier and M. Wille, "Comparison of Transmission Schemes for Framed ALOHA based RFID Protocols", *Workshop on RFID and Extended Network Deployment of Technologies and Applications*, Phoenix, AZ. Jan 2006.

[14] C. Floerkemeier, "Transmission control scheme for fast RFID object identification", *IEEE PerCom Workshop on Pervasive Wireless Networking*, Mar 2006.

[15] Qingsong Peng, Ming Zhang and Weimin Wu, "Variant Enhanced Dynamic Frame Slotted ALOHA Algorithm for Fast Object Identification in RFID System", IEEE.

[16] [Online]. Available: http://www.impinj.com/Indy_RFID_Reader_Chips.aspx

[17] [Online]. Available: http://www.impinj.com/Monza_4_RFID_Tag_Chips.aspx

[18] Chandan Maity and M Vijaybabu, "RTLS in Passive RFID System," in *Proc ASCNT 2009*, pp. 194 - 203, 2009.

[19] B. Zhen, M. Kobayashi and M. Shimizu, "Framed ALOHA for multiple RFID objects identification", *IEICE Transactions on Communications*, vol. E88-B(3), Mar 2005.

[20] Xu Huang, "An Improved ALOHA Algorithm for RFID Tag Identification" *Springer, KES 2006*, Part III, LNAI 4253, pp. 1157 – 1162, 2006.

[21] GENG Shu-qin, GAO Da-ming, ZHU Chao, HE Ming and WU Wu-chen, "An Improved dynamic framed Slotted Aloha Algorithm for RFID Anticollision", ICSP2008 Proceedings, 2008.

[22] EPCglobal Specification for RFID Air Interface, [Online].Available: http://www.epcglobalinc.org/standards/uhfc1g2/uhfc1g2_1_2_0-standard-20080511.pdf

[23] Murali Kodialam and Thyaga Nandagopal, "Fast and Reliable Estimation Schemes in RFID Systems", *MobiCom'06,* September 23–26, 2006, Los Angeles, California, USA.